Realization of the Sensor Web Concept for Earth Science using Mobile Robotic Platforms

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Abstract—In this paper, we discuss the realization of a robotic mobile sensor network that allows for controlled reconfiguration of sensor assets in a decentralized manner. The motivation is to allow the construction of a new system of in-situ science observations that requires higher spatial and temporal resolution models that are needed for expanding our understanding of Earth system change. These observations could enable recording of spatial and temporal variations in environmental parameters required for such activities as monitoring of seismic activity, monitoring of civil and engineering infrastructures, and detection of toxic agents throughout a region of interest. The difficulty in establishing these science observations are that global formation properties must be achieved based on the local interactions between individual sensors. As such, we present a novel approach that allows for the sensor network to function in a decentralized manner and is thus able to achieve global formations despite individual sensor failure, limitations in communication range, and changing scientific objectives. Details on the sensing and control algorithms for controlled reconfiguration will be discussed and results of field deployment will be presented.[1][2]

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1. INTRODUCTION

Sensor networks (or webs) have been shown to be a powerful tool for in-situ Earth science applications ranging from earthquake forecasting to understanding climate change [1]. These networks capitalize on their ability to deploy cheap nodes throughout a region of interest in order to gather information relevant for scientific analysis. Recently, there has been growing interest in mobile networks to deal with the limitations of static networks, including issues of network deployment, coverage, and fault tolerance. However, a number of issues still exist in deploying mobile sensor networks for Earth science applications, including the effectiveness of adapting to the environment and to changing science requirements, balancing power usage, and selecting between communication and control strategies.

To address current limitations, we discuss a natural extension to the sensor web concept that enables controlled reconfiguration of sensor assets for fault-tolerant in-situ sampling. The main motivation behind our approach is to apply decentralized (i.e. local) control algorithms for network deployment while establishing the global sensing capability required for Earth science investigations. The integrated sensing platform, which we refer to as a SpiderMote, combines hardware, in the form of communication/sensor devices (motes), and simple mobility platforms (spiders) for re-positioning sensor devices in response to changes in science demand, sensor failure, and/or communication dropout. This system of mobile sensors is conceptually described as a decentralized network of in-situ sensors. A desired science formation is achieved by defining distances between sensors that correlates with specific topologies that the sensor network should assume.

In most sensor web applications, individual sensor agents collect information about their environment and neighboring agents using peer-to-peer communication. Unfortunately, as the size of the network increases, bandwidth limitations and the absence of feasible communication channels severely limits the possibility of conveying and using global information. Thus, it cannot be assumed that each sensor agent has complete information about the states of every other agent in the network. And yet, a network formation is inherently a global property and, as such, novel solutions must be implemented for the reconfiguration process to successfully occur. Subsequently, in addition to the hardware elements that comprise the SpiderMotes, software control is instituted for adaptive reconfiguration of the network that changes the spatial resolution of the network, in effect establishing a self-adapting sensor network. This occurs in order to maintain the desired science-driven configuration in spite of changes in science demand.

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[1] 1-4244-0525-4/07/$20.00 ©2007 IEEE.

[2] IEEEAC paper #1099, Version 1, Updated December 1, 2006

In this paper, we will discuss realization of the sensor web concept for Earth Science using mobile robotic platforms. In Section 2, we provide an overview of related work. Section 3 discusses the realization of the hardware platform used to construct the sensor web, while Section 4 documents the control algorithms for controlled reconfiguration of the sensor assets. Finally, results of deployment using the mobile robotic platform is discussed in Section 5 with conclusions drawn in Section 6.

2. BACKGROUND

Recently, there has been growing interest in mobile networks to deal with the limitations of static networks. In [2], a system of mobile sensor networks that combines distributed robotics and low power embedded systems is presented. The focus of this work is not on control, but rather on the development of an integrated hardware/software platform. [3] also presents the development of a new type of mobile (robotic) sensor node to meet the constraints of mobile sensor networks. In this work, a hardware paradigm was presented that balances modularity and efficiency in order to perform a navigation task in a complex environment. In terms of control, the problem of controlling multiple, mobile sensor agents in a coordinated fashion has received considerable attention during the last few years (e.g. 4, 5). In these efforts, the underlying assumption has typically focused on having complete knowledge for each individual agent such that the locations and positions of the other agents in the network are known. However, this is not always the case, especially as the number of sensors within the network grows, causing bandwidth and range limitations to invalidate this global assumption. In [6], the design of localized algorithms and the use of a directed diffusion model was presented to deal with the limitations found in assuming complete knowledge. The focus in this effort was not on reconfiguration though, but rather on how to deal with communication limitations arising from the sheer numbers of sensors within the network. There has also been some work that addresses the problem of decentralized control where individual agents move according to limited range potential fields or by averaging orientation rules (e.g. 7, 8). However, these efforts do not allow changes to desired formation and, as yet, little work has been done on how to choose formations in a decentralized and autonomous fashion as a reaction to changes in the environment.

To realize the sensor web concept for Earth Science, our focus is on controlled reconfiguration of sensor assets using mobile robotic platforms. This differs from the concept of mobility in Mobile Adhoc Networks (MANETs) in that controlled mobility provides the network the ability to move sensors intentionally. The problem though is that the manner in which network sensors gain information about other sensors is inherently limited. Communication channels are typically constrained and have bandwidth as well as range limitations. As such, our method is based on representing our network though the use of graph models, where an edge between two nodes (sensors) exists only if these sensors can share information through local interactions. This construct, given a desired science formation, allows us to develop decentralized algorithms for realizing a desired Earth science formation, while guaranteeing that the agents stay connected, that they reach the target science formation in a safe manner, and that they determine their individual locations in the network without access to global information. This decentralized methodology represents the novel nature of our approach.

3. SPIDERMOTE – ROBOTIC SENSOR NETWORK

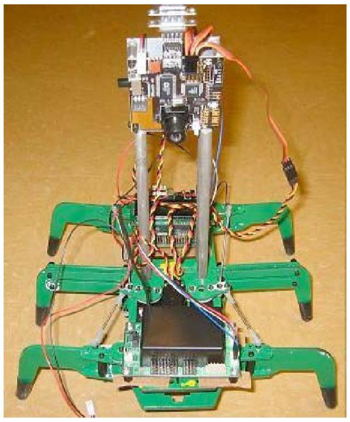

Figure 1. SpiderMote construct for inclusion in the robotic sensor network

We define a sensor node within the network as an integrated sensing platform that combines communication and sensing capability with mobility. The integrated sensing platform, which we refer to as a sensor agent, allows for controlled re-positioning of the sensor devices such that science observations at desired spatial and temporal resolution can be achieved. Specific attributes that must be included in the agent design require the following:

- Linear and rotational velocities of the sensor agent must be controllable.
- Each sensor agent must possess a communication channel such that it has the ability to receive and transmit information to other agents.
- Each sensor agent must possess a sensing channel such that it has the ability to verify the presence and location of other sensor nodes within the network.
- Each sensor agent must have on-board computation such that it can function independently and does not require a centralized host for decision-making.

This generic definition of a node allows us to define the sensor web concept without being limited to the utilization of specific robotic hardware, communication, or sensing technology. Figure 1 depicts our rendition of a sensor agent within the robotic sensor network that qualifies under this definition.

For sensors deployed for Earth Science applications, a key technical difficulty in instituting the sensor web concept is compensating for the non-global characteristic of the network (i.e. a decentralized configuration of sensors that must interface individually to achieve collective behavior). As such, we model our sensor network using graph formalisms [9-10], which allows us to represent the relationship of the sensor agents within the network. The graphs are used to model local interactions between sensors within a planar network, when individual sensor agents are constrained by limited knowledge of other sensor agents. We define our network as consisting of *N* agents, each with identical dynamics and carrying a pre-assigned identification tag $n \in \{1,2,\ldots,N\}$ such that:

$$Agent_n : \{x_n, y_n, \phi_n\} \tag{1}$$

$$\delta_n^i = \sqrt{(x_n - x_i)^2 + (y_n - y_i)^2} \tag{2}$$

$$\psi_n^i = \tan^{-1}\left(\frac{y_n - y_i}{x_n - x_i}\right) \tag{3}$$

$$\theta_n^i = \psi_n^i - \phi_n \text{ so that } \psi_n^i = \theta_n^i + \phi_n \tag{4}$$

where x_n, y_n defines each agent's position and ϕ_n defines the absolute heading, δ_n^i is the distance between $Agent_n$ and $Agent_i$, ψ_n^i is the angle of robot $Agent_n$ to $Agent_i$, and θ_n^i is the relative angle of $Agent_n$ to the heading ϕ_i of $Agent_i$.

As this is a decentralized network of sensors, each agent can communicate to other agents through a communication channel, having a limited range of η. This communication channel has a bi-directional property and is designated as $C_{n\leftrightarrow i}$. In addition, each agent can sense another agent through a sensing channel, having a limited range of γ and a perception cone of ϑ centered around ϕ. The sensing channel $S_{n\to i}$ between agents is a directed channel since, depending on the orientation of the agents' sensing cone, $S_{n\to i} \neq S_{i\to n}$. In other words, although agent *n* may be able to sense agent *i*, agent *i* may not be able to sense agent *n*. Using this construct, we can represent the relationship between agents by a graph in which the vertices of the graphs represent agents, and connected edges are established when agents are within communication or sensing range of each other (Figure 2) such that:

$$\begin{aligned} C_{n\leftrightarrow i} &\Rightarrow \delta_n^i \le \eta \\ S_{n\to i} &\Rightarrow \delta_n^i \le \gamma \end{aligned} \tag{5}$$

This implies that an agent can assume a maximum distance value if it can communicate with another agent, but can only determine absolute distance and orientation if it can sense the other agent. Using this construct, two agents can be represented as having a fully connected relationship within the graph when $\delta_n^i \le \gamma$ and. $|\theta_n^i| \le \vartheta$.

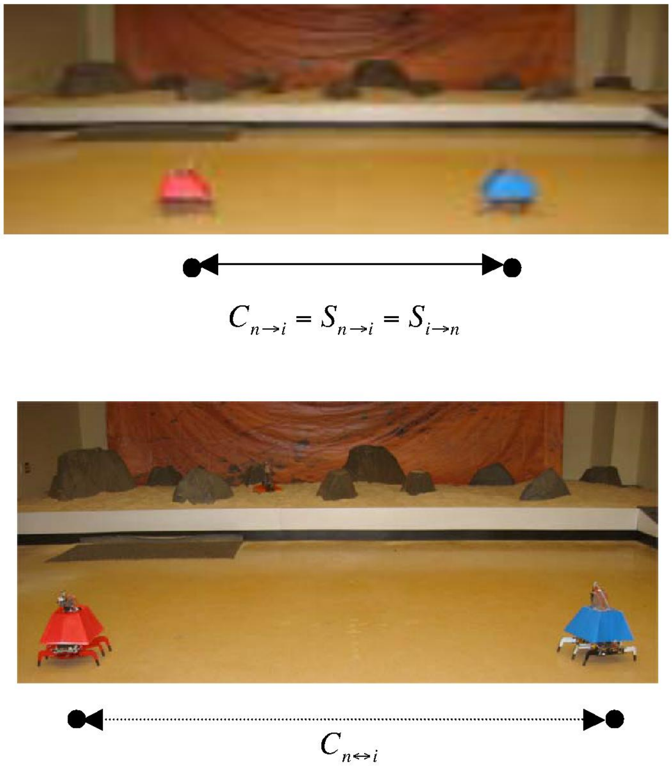

Figure 2. Depiction of two sensor agents and their associated connection graphs

4. RECONFIGURATION OF THE NETWORK

The utilization of a robotic sensor network provides the system the ability to physically change sensor resolution associated with a desired network topology. This driving need can be as a result of changes in science demand, sensor failure, and/or communication dropout. In this section, we discuss our methodology of using decentralized control strategies based on local agent communication schemes to achieve global reconfiguration of the sensor network necessary to change network topology.

We assume that specific formations that define desired spatial resolutions are provided by the scientist after deployment of the network in the field. This network configuration is classified as the desired science formation, which the current network configuration must be reconfigured to in order to align with science demands. We solve the reconfiguration problem by using a limited consensus algorithm [9] (Figure 3) that capitalizes on the knowledge available from both the communication and sensing channels.

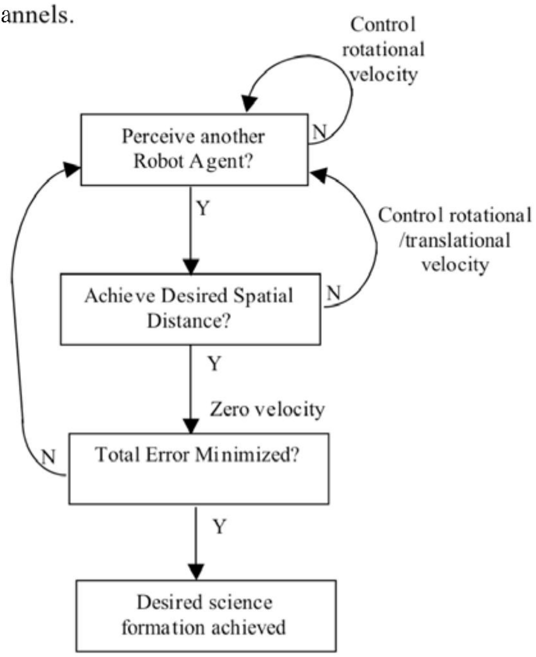

Figure 3. Logic flow for limited consensus control algorithm

In this coordination scheme, each sensor agent *n* tries to maintain a desired distance between other sensor agents present within the network. A network formation error with respect to the desired science formation under consideration is therefore defined as:

$$\begin{aligned}
&\forall n \in \{1, N\}: \\
&\quad \forall i \in \{n+1, N\}: \\
&\qquad \text{if} \quad S_{n\to i} \vee S_{i\to n} \quad Total\_Error+ = \left|\sum \eta - \alpha\right| \\
&\qquad \text{elseif} \quad C_{n\leftrightarrow i} \quad Total\_Error+ = \left|\sum \delta^{i}_{n} - \alpha\right|
\end{aligned}$$

where α designates the desired spatial resolution between sensors, N is the number of sensor agents within the network, and *Total_Error* is the accumulation of distance errors derived from assumed knowledge based on the communication channel and sensed knowledge based on the sensing channel. The goal of the reconfiguration control problem is therefore to change network topology by minimizing the network formation error. To allow each sensor agent to adjust the network topology, decentralized control laws are used to control the distance between robots in the network. Each sensor agent has a controllable translational and rotational velocity, denoted as v_i and ω_i respectively. The goal of the control law it to allow the sensor agents to achieve a desired spatial distances, such that:

$$v_i = \begin{cases} v_0 \cdot sign(\delta^{i}_{n} - \alpha) & \text{if } \left|\theta^{i}_{n}\right| \le \vartheta \text{ and } \delta^{i}_{n} \ne \alpha \\ 0 & \text{otherwise} \end{cases}$$

$$\omega_i = \begin{cases} C_0 \cdot sign(\theta^{i}_{n}) & \text{if } \left|\theta^{i}_{n}\right| \le \vartheta \\ C_0 & \text{otherwise} \end{cases}$$

where v_0, C_0 are constants. In this decentralized method, if no agent is perceived, the agent stops and rotates until it sees another agent(s) in the field. At that point, translational velocity achieves a nonzero value, and the agent moves toward the perceived agent(s) until the desired spatial distance is achieved.

This proposed control strategy enables a desired science formation to be achieved with the use of mobile robotic platforms. Using this approach, the network is autonomously reconfigured from any starting configuration to a desired network formation by executing the trajectories calculated.

5. EXPERIMENTAL RESULTS

For assessment of the methodology, we implement our strategy on the SpiderMote platform, which consists of a mechanical body frame, high torque servos, vision sensor, communication module, and a controller. The skeletal body of the platform is equipped with six legs and has dimensions of [7.5 x 26.5 x 24] cm. Movement of each unit is accomplished using three HI-Tec HS-645MG high torque servos to control movement of three sets of legs. One servo is used to control a set of left legs (front and back) while the other controls a set of right legs (front and back). The third servo is used to control a center set of legs (left and right). When oriented correctly, this center set allows a vertical tilt of the unit from one side to the other. Each servo is oriented in-between its respective set of legs, such that each set is coupled using a push-pull scheme. Thus, as a servo pushes one leg, it simultaneously pulls the other in the same direction. The CMUCam2 vision sensor, with multiple ports for servo control, provide the primary sensor data. Finally, a RidgeSoft Intellibrain™ robotics controller is used to implement the algorithm and provide the control signals for commanding robot movement.

Communication Channel

The wireless control module is capable of transmitting and receiving a single 10 byte message at any given time at a range of up to 150 meters. There are two types of messages: requests and responses. Because messages could potentially be lost, requests are reattempted after a timeout period until the appropriate response is received.

Sensing Channel

The sensing channel consists of visual data retrieved from the CMUCam2 camera mounted on a 15cm boom. Also, each robot is equipped with a color-coded tetrahedral cover, which is mounted below the camera in order to provide each sensor agent with a unique identification tag (Figure 4). This allows the robots to identify each other, and to determine the relative position of other robots that are in camera view. The associated *perception cone* ϑ is approximately $\pi/7$ radians centered around ϕ.

Figure 4. Uniquely tagged SpiderMote sensor agent

To validate our approach, a range of experimental runs were implemented in various terrain environments as depicted in Figure 5. Runs consisted of starting the agents at random initial positions and orientations, and commanding them to achieve a formation having discrete separation distances. The maximum initial separation value between robots was approximately 5 meters. Corresponding final separation distances ranged to approximately 1.5 meters. Average execution time was 2-3 minutes to achieve the desired science formation. In these experimental cases, the robots were able to converge to a final configuration with an accuracy of ± 0.3 meters with respect to the desired separation distance.

Figure 5. Snapshot of experimental run segment

6. CONCLUSIONS

In this paper, we discuss realization of the sensor web concept for Earth Science using mobile robotic platforms. By representing our network though the use of graph models, where an edge between two sensors exists only if these sensors can share information through local interactions, we can develop decentralized control algorithms for realizing a desired Earth science formation. The motivation is to provide a means for sensor agents to achieve distances associated with the target science formation in a robust manner without access to global information. We have integrated our methodology with the SpiderMote system, which acts as our sensor agent within the robotic sensor network. Future work will involve further deployment of the agents in hazardous terrain environments.

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BIOGRAPHY

Ayanna Howard *is an Associate Professor at the Georgia Institute of Technology. Her area of research is centered around the concept of humanized intelligence, the process of embedding human cognitive capability into the control path of autonomous systems. This work, which addresses issues of autonomous control as well as aspects of interaction with humans and the surrounding environment, has resulted in over 60 written works in a number of projects – from autonomous rover navigation for planetary surface exploration to intelligent terrain assessment algorithms for landing on Mars. To date, her unique accomplishments have been documented in over 12 featured articles - including being named as one of the world's top young innovators of 2003 by the prestigious MIT Technology Review journal and in TIME magazine's "Rise of the Machines" article in 2004. Dr. Howard received the IEEE Early Career Award in Robotics and Automation in 2005 and is a Senior Member of IEEE.*

Brian S. Smith *grew up in southern Georgia, graduated valedictorian from Flint River Academy, and went on to earn his BS in Computer Engineering from the Georgia Institute of Technology in 2004. During his undergraduate career, Brian assisted teaching object-oriented programming and a digital design laboratory course. He also assisted Dr. Alan Doolittle for three years at the Advanced Semiconductor Research Facility at Georgia Tech, and assisted Dr. Sung-Kyu Lim for a year in CAD research at the GTCAD laboratory, earning a President's Undergraduate Research Award for research in CAD VLSI applications in 2004. Brian began his graduate work in 2005, focusing on multi-agent control with robotics applications. He is currently building a multi-robot network, while also developing decentralized control algorithms for such networks. His advisors are Dr. Ayanna Howard at the Human-Automation Systems (HUMANS) Lab, and Dr. Magnus Egerstedt at the GRITS Lab.*

Magnus Egerstedt *was born in Stockholm, Sweden. He received the B.A. degree in philosophy from Stockholm University in 1996, and the M.S. degree in engineering physics and the Ph.D. degree in applied mathematics, both from the Royal Institute of Technology, Stockholm, in 1996 and 2000, respectively. He spent 2000–2001 as a Postdoctoral Fellow with the Division of Engineering and Applied Science, Harvard University, Cambridge, MA. In 1998, he was a Visiting Scholar at the Robotics Laboratory at the University of California, Berkeley. He is currently an Associate Professor with the School of Electrical and Computer Engineering, the Georgia Institute of Technology, Atlanta. His research interests include optimal control as well as modeling and analysis of hybrid and discrete-event systems, with emphasis on motion planning and control of (teams of) mobile robots. He has authored over 100 articles in the areas of robotics and controls. Dr. Egerstedt received the CAREER Award from the National Science Foundation in 2003 and is a Senior Member of IEEE.*